DESIGN, DEVELOPMENT, AND UTILIZATION OF A GENERAL PURPOSE AIRBORNE SIMULATOR

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1. INTRODUCTION

Simulators have played a vital role in aeronautical research and development for many years, contributing to the establishment of handling-qualities criteria, pilot training for advanced vehicles, and the solution of specific stability and control design problems. Airborne simulators have been developed to provide motion and visual cues that are more realistic than those available in ground-based simulators. Perhaps even more important, airborne simulators provide stresses and motivation for the pilot that can be attained only in an actual flight environment.

Airborne simulators have taken many forms (refs. 1 and 2), but the term is most often associated with the variable stability and control airplane. The static and dynamic stability characteristics of these vehicles can be varied over a wide range by means of feedback control systems. A variable feel system is usually included that can simulate various control system characteristics.

Two different approaches have been used in the mechanization of variable stability systems. One is the response feedback system that feeds back aircraft response variables as commands to control surface actuators. This generates forces and moments proportional to the responses and artificially changes the aircraft's stability derivatives (refs. 3 and 4). By matching stability derivatives, other airplanes can be simulated. This technique was the most commonly used in variable stability aircraft in the past. The Cornell Aeronautical Laboratory T-33 and the NASA Ames F-100C variable stability airplanes are typical examples.

The other variable stability technique is the model-controlled system (ref. 5). This technique uses, as a model, an airborne computer programed with the equations of motion and aerodynamic coefficients of the airplane being simulated. The pilot flies the model, and feedback loops force the base airplane responses to match the model responses.

The model-controlled system offers several advantages over the response feedback system, such as freedom from lengthy and frequent in-flight calibration, ease of programing, and relative insensitivity to variations and uncertainties in base aircraft weight, inertia, and aerodynamics. The advantages of the model-controlled system are particularly apparent in the simulation of large-inertia,

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low-frequency aircraft because the gains of the response feedback system must be adjusted with great precision in order to cancel the higher frequency dynamics of the base airplane. For simulation of the higher frequency class of vehicles, however, the model-controlled system requires higher gain feedback loops than the response feedback system, in order to keep the error between the model response and the base airplane response small. Consequently, gain limitations, due to noise, instabilities, nonlinearities, and similar effects, will have a greater influence on the simulation capabilities of a model-controlled system than they will on a response feedback system. This means that a response feedback system can simulate aircraft with a higher natural frequency than a model-controlled system can.

The model-controlled system is a relatively new approach to variable stability design. It has been used in variable stability helicopters by the National Research Council of Canada and the NASA Langley Research Center. Cornell has used it to simulate low-frequency longitudinal modes with their B-26 variable stability airplane.

In 1962, the NASA Flight Research Center made a survey of future requirements for airborne simulators. This study indicated a need for a variable stability airplane suitable for simulating vehicles of the supersonic transport class and for performing general handling-qualities research. In June 1964, a contract was awarded to Cornell Aeronautical Laboratory for the implementation of the general purpose airborne simulator. This entailed the design, fabrication, and installation of a variable stability system in a Lockheed JetStar transport.

Installations were completed in June 1965, preliminary ground checks finished in September, and flight tests started shortly thereafter. Checkout and expansion of the capabilities of the general purpose airborne simulator will continue through the spring of 1966. This report discusses the design features, initial development, technical details, and proposed utilization of the vehicle.

2. GENERAL FEATURES

The general purpose airborne simulator is a variable stability and control Lockheed JetStar (fig. 1) with a wide range of simulation capabilities. These capabilities include all aircraft rigid-body modes and flight-path matching for climbout and descent simulations. It is the first variable stability airplane to utilize a model-controlled system as the primary means of simulating all aircraft modes. A variable feel system permits simulation of a wide range of control feel characteristics. Figure 2 shows the general arrangement of the simulation equipment in the JetStar. The servos of the variable feel system were located as close to the cockpit controls as possible. The electronics of the simulation system provide circuitry for a model-controlled system, response feedback system, and variable feel system. An airborne analog computer is installed for use with the model-controlled system. A console for a test engineer is located between the electronics rack and the airborne analog computer. This console provides switches, potentiometers, and instruments for monitoring the simulation and changing configurations in flight. A data-acquisition system consisting of oscillograph recorders and signal-conditioning equipment is located in the aft portion of the cabin. Control surface and throttle servos have been installed parallel to the standard JetStar flight control system for simulation purposes.

Figure 3 is a view of the cockpit area. The left-hand station is for the evaluation pilot. The instrument panel on the left is easily removable, and all instruments are direct-current or servo-driven. A simulation throttle lever is located beside the standard JetStar throttles to provide the test pilot with control over the thrust of the simulated vehicle. The evaluation pilot's controls are connected to the variable feel system. This system senses pilot forces, and electrohydraulic servo actuators position the controls according to the programed gradients. Hysteresis, breakout force, and linear and nonlinear force versus deflection functions can be programed. Bobweights, downsprings, and trim changes can also be represented. The right-hand pilot station is for the safety pilot. His controls are always connected to the standard JetStar flight control system.

2.1 Model-Controlled System

Figure 4 illustrates the general purpose airborne simulator concept using the model-controlled system. The test-pilot controls send inputs to the variable feel system, which, in turn, feeds signals to the analog computer. The airborne computer is programed with a mathematical model of the aircraft to be simulated. This computer has the capability for linear and nonlinear three-, five-, and limited six-degree-of-freedom models. The computer outputs are the responses of the simulated aircraft. These responses are sent to the test pilot's display panel and the model-control circuitry. The model-control circuits form error signals by comparing the computer responses to the JetStar responses measured by the sensors. The error signals are sent as commands to the surface and throttle servos that cause the JetStar to follow the model.

Figure 5 shows the longitudinal feedback loops being used in the model-controlled system. Angle of attack is fed back to the elevator and used to increase the short-period closed-loop frequency for good model following. Studies have indicated that the closed-loop frequency of the general purpose airborne simulator must be at least 1 1/2 times that of the model for satisfactory model following. The angle-of-attack rate feedback provides the desired closed-loop damping. Studies indicate that short-period damping ratios of the closed loops should be approximately 0.5.

Phugoid and flight-path following are performed by feeding back altitude and altitude rate to the elevator and velocity to the throttles. All of these loops affect the closed-loop phugoid frequency and damping. The loop gains needed for good model following have been arrived at empirically from analog-computer studies. These studies also show that all feedback quantities being used should be followed simultaneously for best results.

The lateral-directional loops are similar in concept to the longitudinal loops. They are illustrated in figure 6. The lateral-directional modes use β feedback to control Dutch roll frequency, $\dot{\beta}$ feedback to provide Dutch roll damping, roll-rate feedback to control the roll mode, and bank-angle feedback to stabilize the spiral mode.

2.2 Response Feedback System

The response feedback method of variable stability airplane simulation uses feedback loops to effectively change the base airplane's stability derivatives to match those of the aircraft being simulated. Signals from sensors that measure airplane responses are sent to the control surface servos to produce deflections proportional to the airplane responses. If an elevator deflection proportional to angle of attack is generated, it will provide a pitching moment proportional to angle of attack and effectively change M_{α} of the base airplane.

In a similar fashion, other response variables can be fed back to artificially change most of the stability derivatives. The feedback gain in each loop is varied to provide the effective stability derivative desired. However, to accurately simulate a specific derivative, the aerodynamic derivatives of the base aircraft and the gains of the feedback control system must be known accurately. This makes extensive in-flight calibration necessary. Usually, these calibrations must be repeated for each change in base aircraft flight condition and simulated aircraft configuration. However, the response-feedback technique is capable of simulating higher airplane frequencies than the model-controlled technique.

Little additional hardware is needed to implement the response feedback system in the general purpose airborne simulator, since the feedback loops of the response feedback system are similar to the feedback loops of the model-controlled system. This can be seen in the diagram of the angle-of-attack feedback channel in figure 7. All sensor signals are sent along dual paths: one goes to a summer to form error signals for model-controlled system operation, the other goes directly through a response feedback system gain potentiometer to the simulation servo surface actuators. The other feedback channels are similar in concept to the angle-of-attack channel.

2.3 System Flexibility

Many feedback loops are included in the JetStar system in addition to those already discussed. Physical and geometric constraints often do not permit a variable stability airplane to match exactly all motion variables of the simulated vehicle. The additional feedback loops permit flexibility in choosing what responses will be matched in situations when they cannot all be matched. Feedback loops incorporated in the general purpose airborne simulator are:

Controller	Feedback variables
Elevator	h, $\dot{h}$, ΔV, $\dot{V}$, n_z, n_{z_x}, α, $\dot{\alpha}$, Θ, q, $\dot{q}$
Aileron	φ, p, $\dot{p}$, β
Rudder	β, $\dot{\beta}$, n_y, n_{y_x}, r, $\dot{r}$
Throttle	ΔV, $\dot{V}$

Additional simulation flexibility is provided by the system interconnections shown in figure 8. The analog computer interfaces with the control, display, and data-acquisition systems through patchable connections. This allows almost any signal available in these systems to be routed through the computer, where it may be conditioned, filtered, or routed directly to another portion of the general purpose airborne simulator system.

Another contribution to system flexibility is the data distribution panel. All system signals are available at this panel. It has patchable connections to all recording channels for easy setup of the recorders and additional trunks are provided to the airborne computer.

2.4 Simulation Control System

Successful conversion of a standard-production aircraft into a safe and useful airborne simulator depends to a large extent on proper selection of the control system actuators. For the general purpose airborne simulator, various considerations determined the physical characteristics of the actuators, but in no instance are the surface actuators allowed to apply more hinge moment than can be applied by the pilots of an unmodified JetStar. This limitation is a minimum requirement for safe operation, since the airborne simulator will be restricted to the flight envelope of the unmodified airplane.

The actuators were chosen for low friction and high frequency response. Flight tests have indicated that they have the following performance: the elevator servo has a natural frequency of 10 cycles per second and a damping ratio of 1; the aileron servo has a natural frequency of 7 cycles per second and a damping ratio of 0.8; the rudder servo has a natural frequency of 6 cycles per second and a damping ratio of 0.6. Surface position and hydraulic pressure across the servo are fed back electrically to stabilize the servo loops. Special circuits automatically disengage the simulation servos when critical parameters exceed preset levels. This quickly reverts the airplane to the normal JetStar configuration for ease of recovery.

3. FLIGHT-TEST DEVELOPMENT

At present, the aircraft is in the initial flight-test development stage. The general approach followed in the flight tests has been to choose one flight condition for most of the simulation-system testing: a Mach number of 0.55 at an altitude of 20,000 feet. The feedback loops were used to systematically vary the closed-loop dynamics until gain limitations due to system noise or instability were reached. A number of conditions were then set up in the model-controlled-system simulation mode using a simple aircraft model. This procedure exercised most of the simulation systems, pointing out any serious defects or areas requiring further development. At the same time, it gave a good indication of the simulation fidelity under model-controlled system operation and the influence of variations in closed-loop response on the simulation.

As previously discussed, the JetStar with its feedback loops closed must have good damping and a natural frequency higher than the airplane being simulated for satisfactory model following. Figure 9 illustrates some representative data obtained during loop-closure tests. Note that the frequency and damping shown is that of the JetStar plus the feedback control loops, not that of the model.

At first, the closed-loop damping ratio was restricted to approximately 0.2 because of noise in the $\dot{\alpha}$ and $\dot{\beta}$ feedback loops. A natural frequency satisfactory for transport simulation was attained from the start. Subsequent flights with filters in the $\dot{\alpha}$ and $\dot{\beta}$ loops attained better damping levels, as can be seen in figure 9. Dutch roll damping was still below the design goal, but it has proved to be adequate. These data indicate that the complete model-controlled system, at the present stage of development, can simulate longitudinal short-period natural frequencies as high as 1 cycle per second and Dutch roll natural frequencies as high as 0.3 cycle per second. This is based on estimates that the closed-loop frequency must be at least 1 1/2 times that of the model. Flight tests also indicate that roll-mode time constants as small as 0.20 second can be simulated.

These capabilities comfortably exceed the expected characteristics for supersonic transport aircraft. Also, expansion of the JetStar flight tests to higher dynamic-pressure conditions and additional development work will lead to higher closed-loop frequencies and increase the model-following general-purpose research capabilities.

Figures 10 and 11 show, respectively, examples of angle-of-attack and angle-of-sideslip model following obtained early in the flight-test program. The model following was acceptable, even though there was an approximate time lag of 0.2 second between the model and JetStar responses. Such time lags would not be noticeable to a pilot in normal flying. However, better model following is expected as the vehicle development proceeds.

4. UTILIZATION OF THE GENERAL PURPOSE AIRBORNE SIMULATOR

Initial utilization of the general purpose airborne simulator will emphasize validation of its capabilities with a simulation of the XB-70 airplane. Most of the flights to date have been devoted to system tests and development. However, as the systems required to simulate various aircraft modes are checked out, XB-70 characteristics will be programed and the development continued. Refinements will be made until good correlation is obtained between the airborne simulator and XB-70 flight data. XB-70 pilots will then fly the JetStar and compare its simulation to their experience in the actual aircraft. This will provide information for further development and experience in simulating large supersonic aircraft in subsequent programs.

The research areas being considered for the general purpose airborne simulator emphasize transport research, since relatively little flight data directed toward transport handling qualities are available. Practically all previous work with variable stability airplanes has been fighter- or bomber-oriented.

The first research area being considered is the determination of optimum augmented characteristics and acceptable unaugmented characteristics for supersonic transport and XB-70 type vehicles. This includes study of optimum and minimum stability levels, with and without stability augmentation in smooth and rough air.

The second research area is the evaluation of new flight control configurations, such as adaptive versus fixed gain.

Third, is the simulation of specific vehicles, such as the XB-70 and the Concorde, Boeing, and Lockheed supersonic transports. As previously mentioned, large supersonic aircraft will be considered first. Later, subsonic transports may be simulated, such as the C-5A and the Sky-Bus proposals.

Fourth, is the investigation of general handling-qualities criteria. A broad range of vehicles can be studied by the JetStar, but transports will be emphasized.

The final item is the validation of ground-based simulators. The JetStar can be used to make direct comparisons between flight and ground results.

The types of studies that the general purpose airborne simulator will perform will be similar to those conducted by NASA and Cornell in the past. However, it will be possible to accomplish programs with greater speed and accuracy as a result of the model-following technique and flexibility of the systems in the JetStar. In particular, simulation of specific aircraft will be accomplished much more easily. Five-degree-of-freedom studies with constant velocity are expected to be the most common utilization. Six-degree-of-freedom simulations will be used for significant flight segments such as subsonic climb, transonic acceleration, or high-speed cruise. Such a six-degree-of-freedom capability is expected to be operational by December.

A future expansion currently being planned for the JetStar is the inclusion of digital equipment to convert the present computer to a hybrid computer. This modification would enable very complex six-degree-of-freedom models to be programed.

5. CONCLUDING REMARKS

The general purpose airborne simulator is a variable stability and control aircraft with a broad range of capabilities. A model-controlled system is the primary means of simulation, since it offers reduced flight calibration time, ease of programing, and increased accuracy. Flexibility has been emphasized in system design to insure a versatile vehicle. Initial flight tests tend to confirm the advantages of the model-controlled system and the general purpose capabilities of the vehicle. Expected utilization will emphasize supersonic transport and XB-70 applications.

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NOTATION

h	altitude
M	Mach number
M_{α}	static longitudinal-stability derivative
n_y	lateral acceleration at center of gravity
n_{y_x}	lateral acceleration at position x
n_z	normal acceleration at center of gravity
n_{z_x}	normal acceleration at position x
p	roll rate
q	pitch rate
r	yaw rate
V	velocity
ΔV	incremental velocity
α	angle of attack
$\Delta\alpha$	incremental angle of attack
β	angle of sideslip
δ_a	aileron deflection
δ_e	elevator deflection
δ_r	rudder deflection
δ_t	throttle deflection
ζ	damping ratio

Θ	pitch angle
φ	roll angle
ω_n	natural frequency (undamped)

A dot over a quantity indicates the derivative with respect to time.

Figure 1.-- Photo of NASA general purpose airborne simulator, the Lockheed JetStar.

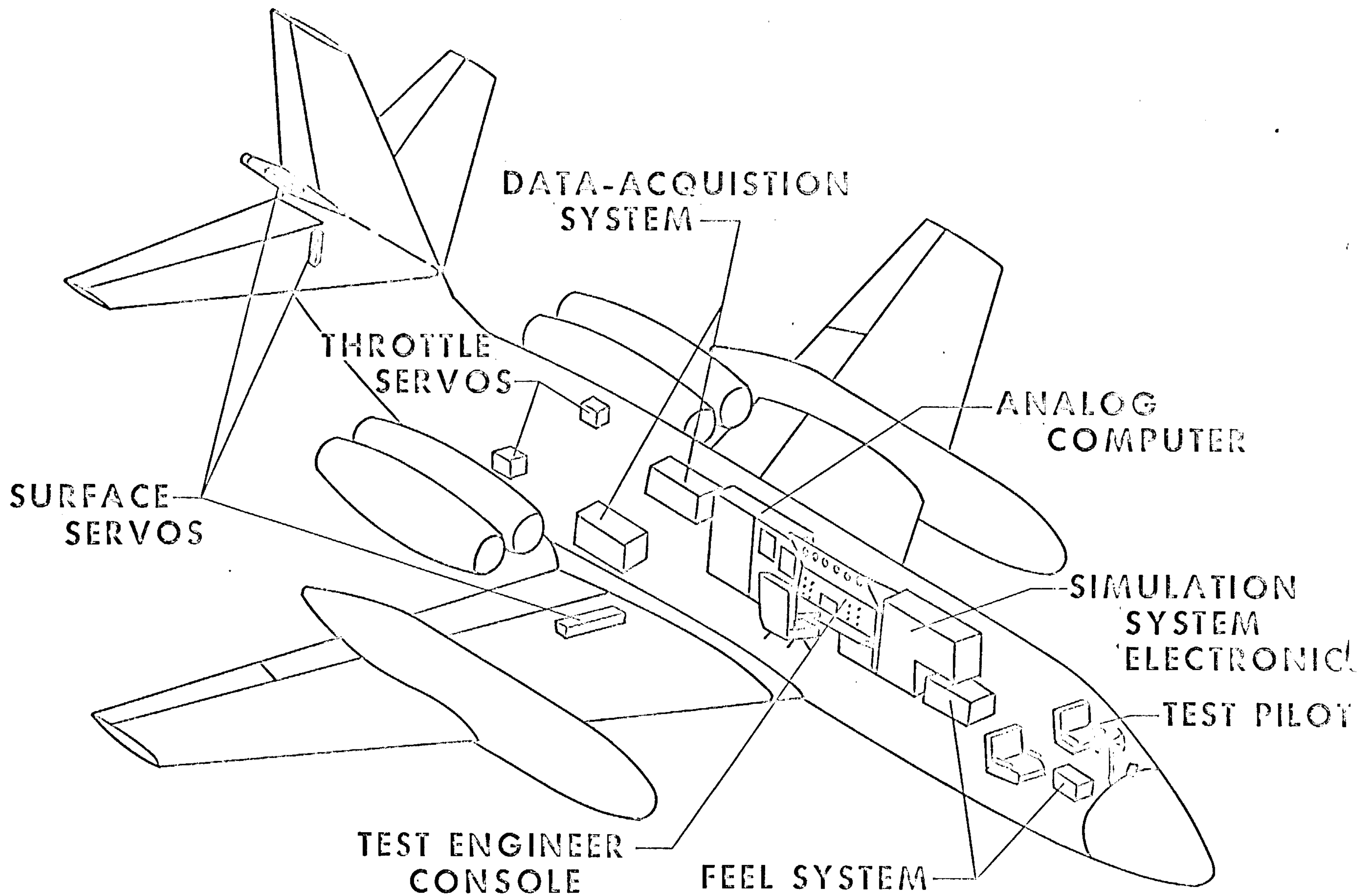

Figure 2.– Layout of general purpose airborne simulator systems.

NASA
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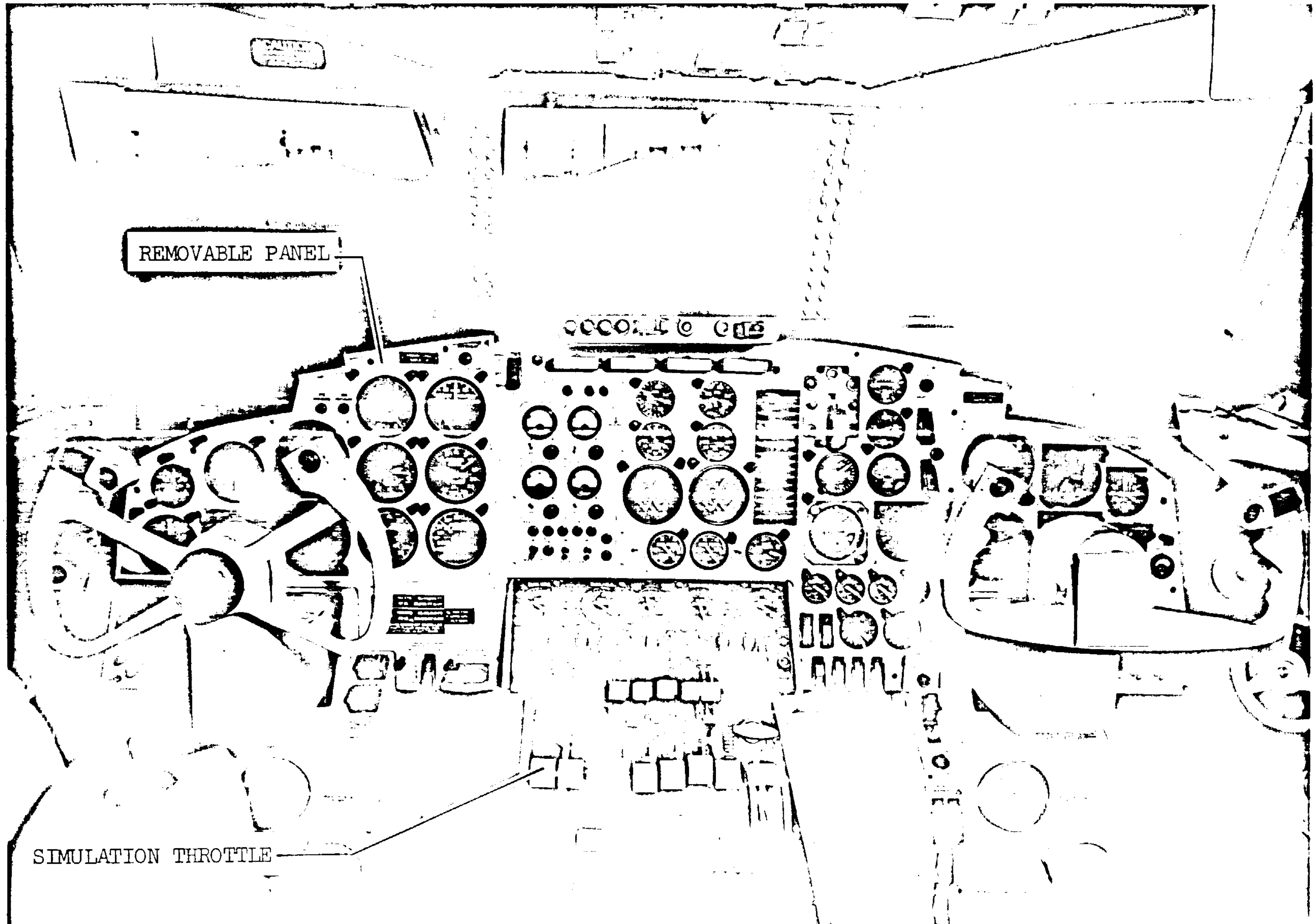

Figure 3.– Cockpit of general purpose airborne simulator.

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Edwards, California

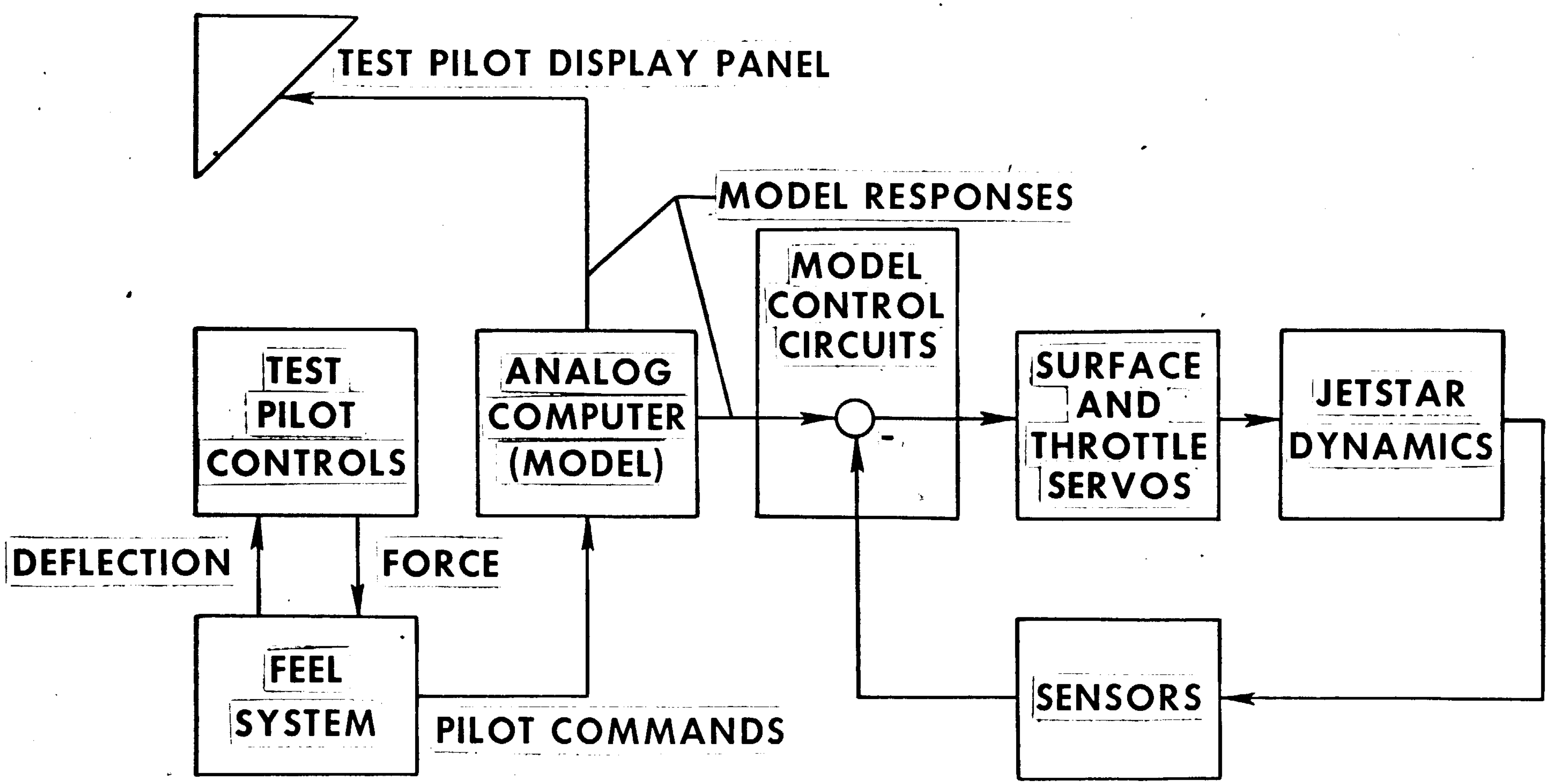

Figure 4.– Model-controlled system of the general purpose airborne simulator.

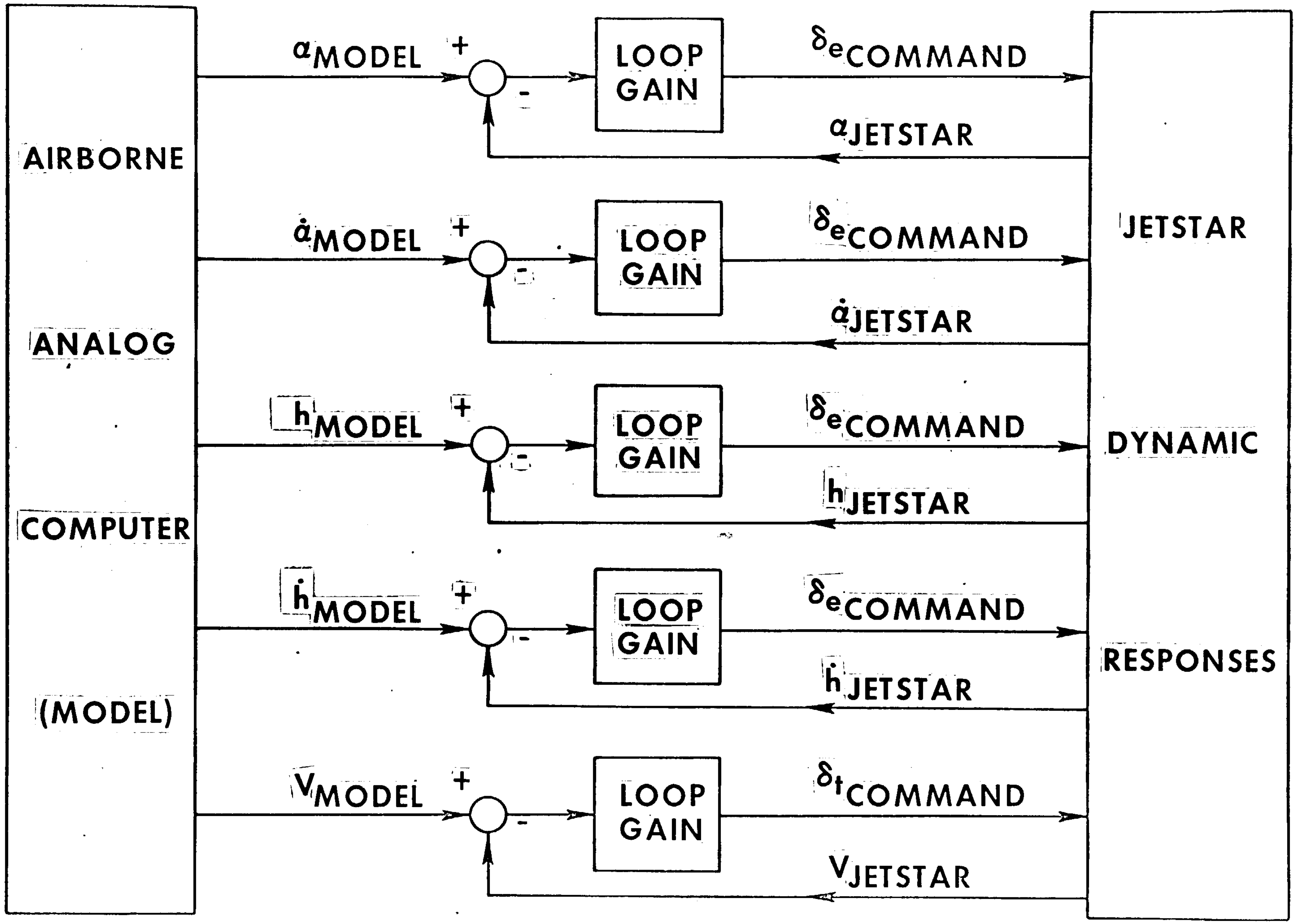

Figure 5.- Longitudinal loops of the model-controlled system.

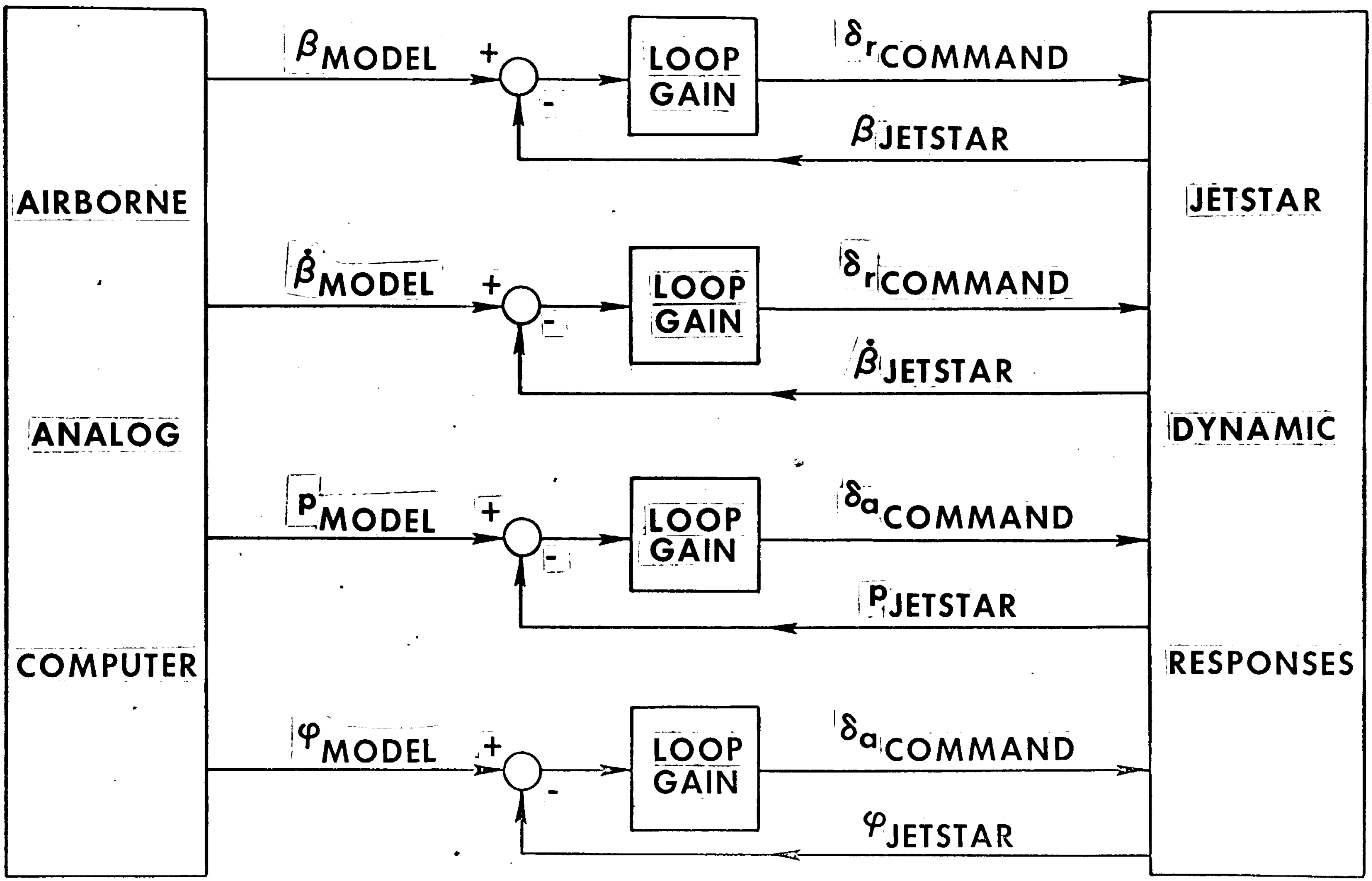

Figure 6.– Lateral-directional loops of the model-controlled system.

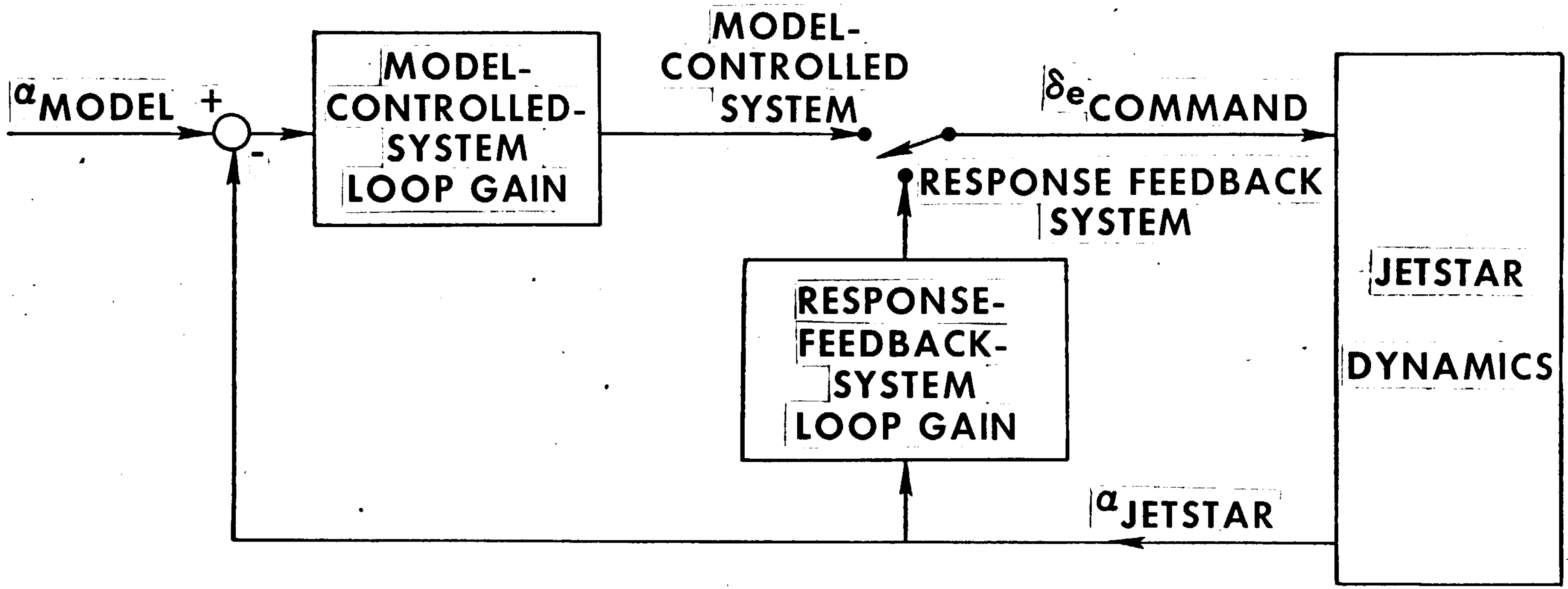

Figure 7.– Angle-of-attack feedback channel of the general purpose airborne simulator.

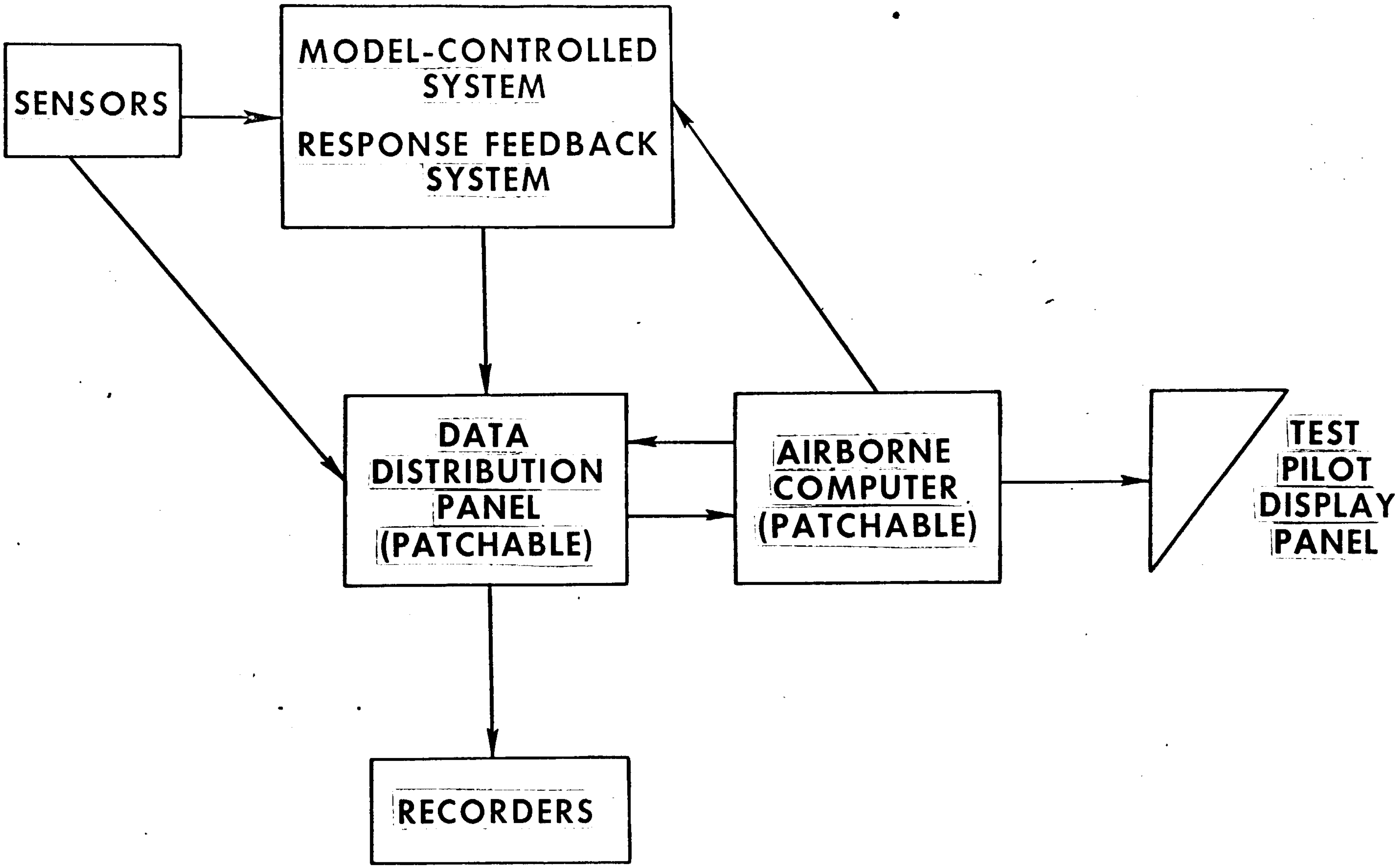

Figure 8.– Connections available between systems in the general purpose airborne simulator.

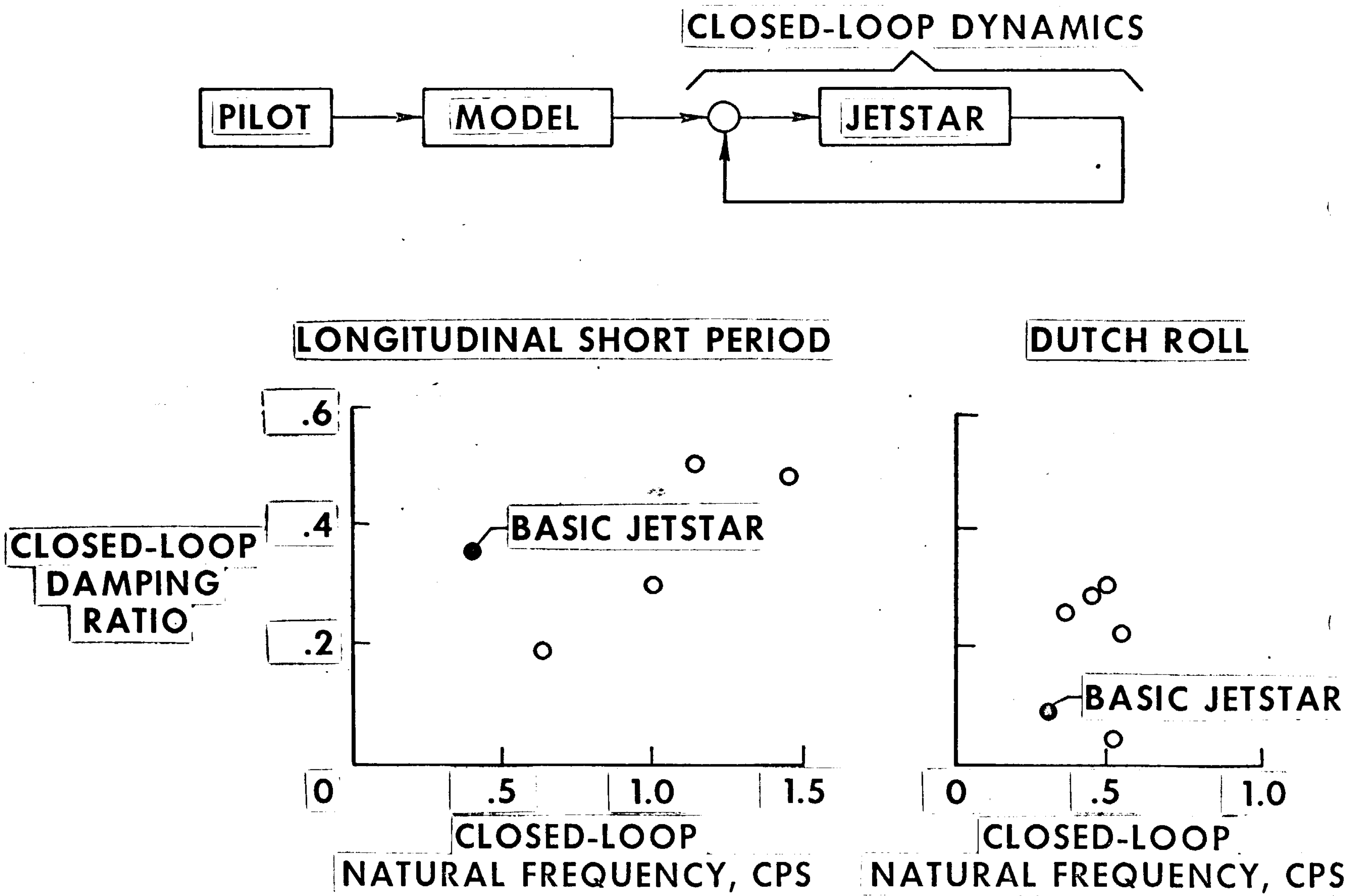

Figure 9.- Closed-loop flight-test results from the general purpose airborne simulator. JetStar flight condition: $M = 0.55$, $h = 20{,}000$ feet, average weight = 30,000 pounds.

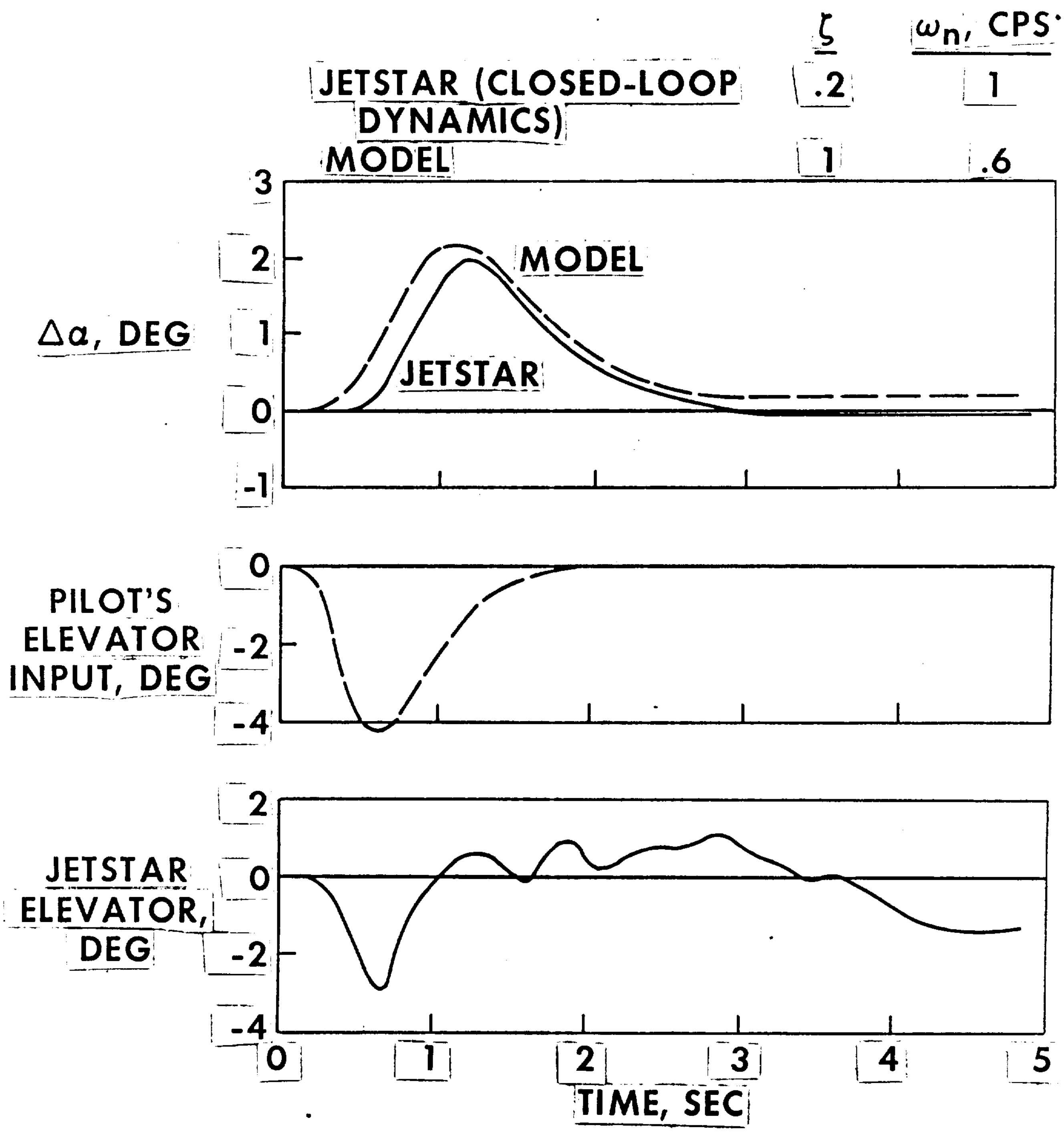

Figure 10.– Flight test time history of angle-of-attack model following.

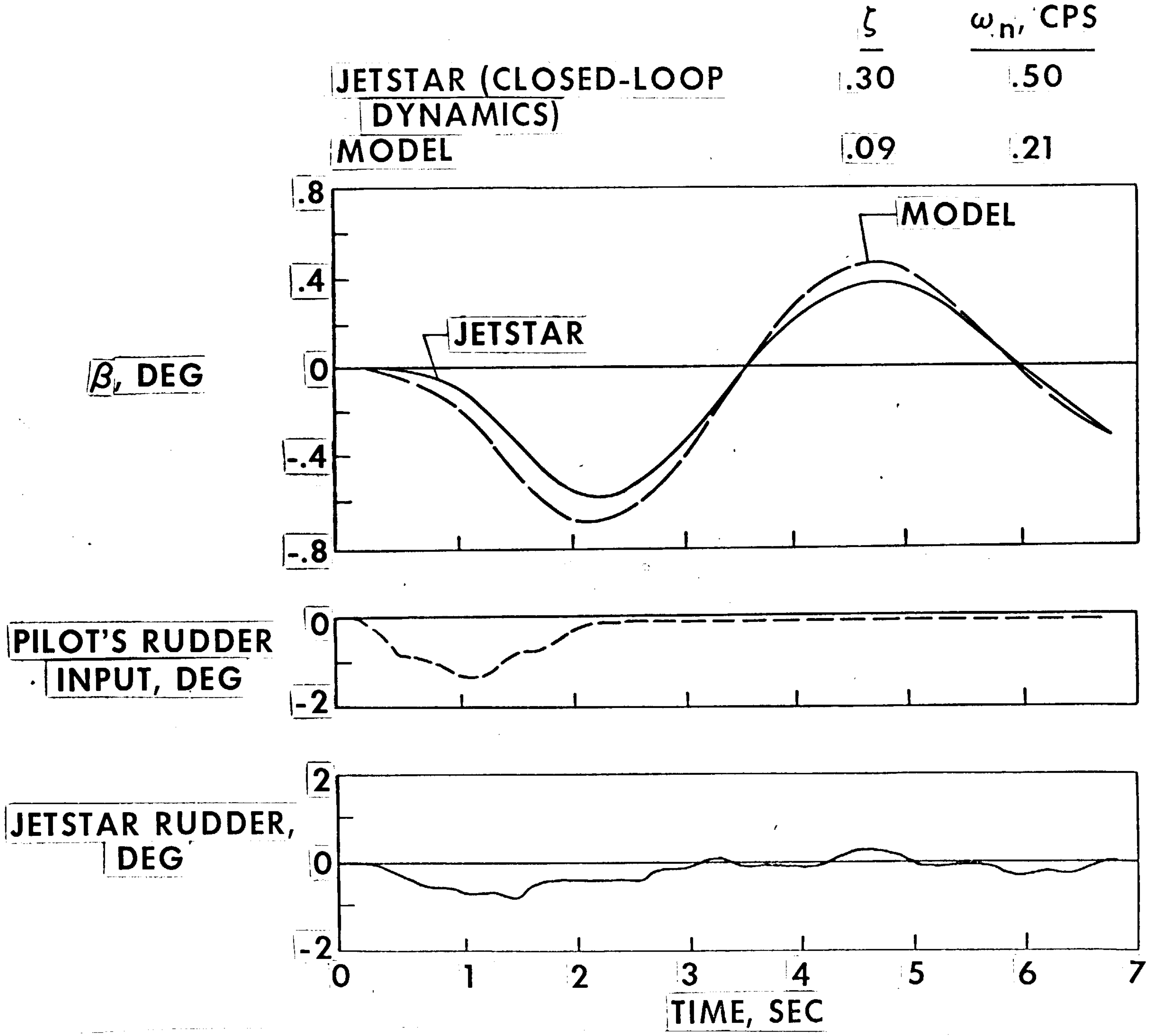

Figure 11.– Flight test time history of angle-of-sideslip model following.